11. Monitoring

11.1 THE NEED FOR MONITORING

11.1.1 EPA Disposal Standards

Predictive models are used in the design of the WIPP. Computer simulations of the repository environment are used to provide information to engineers and scientists during the design of the facility. The computer simulations use analytical, empirical, and statistical predictive models to simulate various interconnected aspects of the disposal system. These computational simulations and predictive models reflect the state of knowledge of the characteristics of the disposal system at the site, and include, for example, chemical, physical, radiological and biological components.

Analytical techniques are highly useful in predictive modeling due to the conceptual nature of their formulation. However, such models are based on the current state of knowledge of highly complex systems and are susceptible to imperfect understanding of individual or systemic components. A result of this imperfect state of knowledge is the introduction of uncertainty into the model results. Thus, it is desirable to augment predictive models with empirical data to lower inherent modeling uncertainties.

Since the predictions associated with long-term compliance have inherent uncertainty, the final disposal standards issued by EPA in 1985 included a provision requiring monitoring of disposal systems to assure their compliance. EPA surveyed the capabilities and expectations of long-term monitoring approaches. As explained in the preamble to the 1985 disposal regulations (50 FR 38081, September 19, 1985):

> Evaluating this information led the Agency to several conclusions:
>
> (1) Perhaps most importantly, the techniques used for monitoring after disposal must not jeopardize the long-term isolation capabilities of the disposal system. Furthermore, plans to conduct monitoring after disposal should never become an excuse to relax the care with which systems to isolate these wastes must be selected, designed, constructed, and operated.
>
> (2) Monitoring for radionuclide releases to the accessible environment is not likely to be productive. Even a poorly performing geologic

repository is very unlikely to allow measurable releases to the accessible environment for several hundreds of years or more, particularly in view of the engineered controls needed to comply with 10 CFR part 60 [for facilities subject to regulation by NRC]. A monitoring system based only on detecting radionuclide releases -- a system which would almost certainly not be detecting anything for several times the history of the United States -- is not likely to be maintained for long enough to be of much use.

(3) Within the above constraints, however, there are likely to be monitoring approaches which may, in a relatively short time, significantly improve confidence that a repository is performing as intended. Two examples are of particular interest. One involves the concept of monitoring groundwater sources at a variety of distances for benign tracers intentionally released to the groundwater in the repository; this approach can evaluate the delay involved in groundwater movement from the repository to the environment and can serve to validate expectations of the performance expected from the system's natural barriers. Another concept involves monitoring the small uplift of the land surface over the repository in order to validate predictions of the system's thermal behavior. Both of these approaches can be carried out without enhancing pathways for the wastes to escape from the repository.

Based on these conclusions and the public comments on this question, EPA decided to include an assurance requirement in 40 CFR part 191 for long-term monitoring after disposal: "Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring." (§191.14(b)).

To support post-closure monitoring and to provide a baseline for comparison with future measurements, the monitoring of parameters which are important to the long-term integrity of the disposal system must also be performed prior to closure. This type of monitoring can provide important information about the disposal system and can contribute to a better understanding of how the disposal system is likely to perform after closure. Furthermore, such information can be used to verify assumptions (about the disposal system) which form the basis for PA.

The word "monitoring" is not defined in 40 CFR part 191. However, monitoring is considered as a form of active institutional control. According to §191.12(f), "active institutional control means:.....(4) monitoring parameters related to disposal system performance." §191.14(a) requires active institutional controls to be "maintained for a long a period of time as is practicable after disposal," but contributions of active institutional controls in PA are limited to a maximum of 100 years. In the preamble to 40 CFR part 191, EPA noted that many commenters believed "a few hundred years" as originally proposed was too long a period for active institutional controls to be effective and consequently limited reliance on active institutional controls to 100 years (50 FR 38080). By inference, reliance on monitoring for more than 100 years was not contemplated in the final rule.

11.1.2 RCRA Regulations

40 CFR part 264 contains the standards for operating hazardous waste treatment, storage and disposal facilities. Subpart F specifies the requirements for monitoring. It describes the monitoring program which must be conducted, the hazardous constituents to be monitored for, and the applicable groundwater protection standards. The thrust of Subpart F is to detect any hazardous components of the waste released to groundwater.

Subpart F also contains a waiver to its requirements for monitoring. §264.90(b)(2)(vii) states that the Administrator can waive the requirements of Subpart F if it is shown to a reasonable degree of certainty that the facility will not allow hazardous constituents to migrate beyond the outer containment layer prior to the end of the post-closure care period. Since this waiver is essentially describing the PA for the site, a waiver to the monitoring described in Subpart F could be granted. However, if ground-water monitoring wells are employed during the disposal phase, then the wells must be operated during a thirty-year post-closure phase, as well (EPA86).

40 CFR part 268 contains the regulations and requirements for land disposal of hazardous wastes. §268.6 describes petitions to allow land disposal of prohibited waste. The No-Migration Variance Petition (NMVP) requires a monitoring plan to detect migration at the earliest practicable time when disposing of prohibited waste in ground. This plan must include the following information:

- the media monitored,

- the type of monitoring conducted,
- the location of the monitoring stations,
- the specific hazardous constituents to be measured,
- the implementation schedule,
- the equipment used,
- the sampling and analysis techniques, and
- the data recording and reporting procedures.

Since the monitoring requirements specified in 40 CFR part 268 are general in nature, sufficient flexibility should be available to develop a monitoring program which complies with this regulation and the long-term monitoring requirements of 40 CFR part 194.

11.2 PRE-CLOSURE MONITORING

In order for the WIPP to comply with the requirements of 40 CFR part 194, predictive modeling techniques must be used. EPA has specified that analyses need to be performed to identify the parameters subject to pre-closure monitoring (§194.42(d)). The required analysis will define which additional parameters will be subject to pre-closure monitoring. The information obtained from these monitoring activities will contribute to a better understanding of how the disposal system is likely to perform after closure.

As discussed above, the objective of the monitoring assurance requirement in 40 CFR part 191 is to detect "substantial and detrimental deviations from expected performance" after disposal. In order to have a basis for future measurements, an adequate pre-closure baseline must be established though measurements taken prior to repository closure. This pre-closure monitoring is not for the same purpose as much of the pre-operational monitoring undertaken at the WIPP site by DOE and the New Mexico EEG.

11.2.1 Pre-Disposal Monitoring to Support Operations and Closure

EEG was authorized to conduct independent site monitoring under the July 1981 Agreement for Consultation and Cooperation between the State of New Mexico and DOE ("the Agreement"). EEG developed a preoperational environmental monitoring plan for the WIPP site in 1984 (SPI84).

According to the Appendix A of the Supplemental Stipulated Agreement to "the Agreement" dated December 28, 1982 (SPI84), EEG will conduct:

- preoperational monitoring
- monitoring during the operational phase
- monitoring during and at least two years after the decommissioning and decontamination phase
- limited post-operational phase monitoring (i.e., after termination of decommissioning and decontamination) for not less than five years

For a number of years, DOE has also conducted a program to define the environmental baseline for the WIPP site (DOE93, DOE94). The Operational Environmental Monitoring Program (OEMP), which is intended to continue during operation and through decommissioning.

A major element of the nonradiological monitoring is meteorology which involves measurement of wind speed, wind direction, temperature, dew point, and precipitation. Seismic activity is measured routinely at four stations around the WIPP site.

11.2.2 Pre-Closure Monitoring to Support Assurance Requirements

The EPA compliance criteria (§194.42(c)) requires preclosure monitoring of significant parameters as identified by an analysis by DOE. The analysis will identify parameters that affect the disposal system's ability to contain waste or the ability to verify predictions about its future performance.

The following is a discussion of several parameters which could potentially be identified as significant for monitoring. Brine-related parameters, room closure, subsidence, and geophysical monitoring are discussed because they are examples of parameters that can be monitored at a mined facility and may already be monitored by DOE to support operational activities or meet other regulatory requirements. Consideration of the many parameters that can be monitored in association with a mined facility supported the Agency's decision to require an analysis of parameters that can be monitored to determine those with significance to the containment of waste within the disposal system.

11.2.2.1 Brine quantity, flux composition, and spatial disposition

EPA has reviewed DOE and DOE contractor reports on in situ tests and repository monitoring to characterize brine flow into the repository. This work has been broken down into three specific programs:

- Large-scale brine inflow test (Room Q)
- Brine sampling and evaluation program (BSEP)
- Small-scale brine inflow experiments

Large-Scale Brine Inflow Test

The Room Q test which operated from July 1989 until May 1994 was designed to obtain information on brine inflow into the WIPP from an excavation which approached the scale of a repository disposal room. Room Q was a horizontal cylindrical excavation 108 meters long and three meters in diameter sealed with two bulkheads. The rate of brine seepage into the closed room was measured by various collection methods. During the 1,800-day test approximately 210 liters of brine were collected.

Brine Sampling and Evaluation Program

The BSEP program, which has been conducted since 1985, collects general repository wide information on brine inflow. The three program elements include:

- brine flow to boreholes
- brine flow to underground openings
- laboratory measurements of brine chemistry and brine content of rock samples

A total of 119 boreholes have been monitored for various periods of time since 1984. Of these, 51 never produced brine or stopped producing brine during the monitoring period. As of September 1994, 105 of the holes had been dropped from the monitoring program due to contamination from construction activities or because the holes were lost to mine related events (HOW94). Thirteen boreholes have continuously produced brine with typical yields being on the order of tens of milliliters per day.

Brine seeps on the walls of the excavated surfaces are also monitored. Mapping studies have shown that clay seams rather than the halite and anhydrite are the preferential brine sources.

Small-Scale Brine-Inflow Experiments

This experimental work, which was conducted from September 1987 through June 1993, involved monitoring brine inflow into 17 boreholes ranging in diameter from 5 to 90 centimeters (HOW94). Some brine inflow was observed in all but two of the holes.

<u>Room Closure</u>

One of the defining characteristics of the WIPP repository is closure of the disposal rooms due to creep of the salt. Room closure includes any displacement change induced by mining. Roof sag and floor rise are examples. Displacement is the simplest and most reliably measured geotechnical variable associated with repository excavation and operation. Generally displacements are largest near the most recently excavated room and diminish roughly linearly with distance from a room. A large number of displacement measurements have been made at WIPP for the purpose of code validation and calibration. These measurements have been made at the surface of excavated rooms and in boreholes, also excavated in salt. Creep of salt induces a time-dependency in the displacement field about the repository. Other rock types, for example, anhydrite, are not considered to creep significantly. Displacement change in these rock types ordinarily occurs concurrently with excavation. However, salt creep constrains the motion of adjacent strata that otherwise do not creep. Displacement measurement by itself is not sufficient for model validation. Stress measurements are needed in addition to displacement measurements. Other mechanical measurements and observations are also possible within the scope of pre-closure monitoring of repository rooms.

Displacement Measurements

Instrumentation for displacement measurement commonly consists of: (1) reference points directly attached to excavation walls, roof and floor, and (2) reference points anchored in boreholes (borehole extensometers). The latter provide for displacement measurement within the rock mass enclosing an excavation. Extensometer lengths of 100 ft (30 m) are common.

Instrument readings may be direct and mechanical, for example, by dial gauge. Reproducibility of readings is generally a few thousandths of an inch (a few hundredths of a millimeter). The same is true of measurements at excavation walls which are often done by precision tape measurements between walls and between roof and floor.

Displacement measurements are not only the most reliable measurements made in the realm of geotechnical monitoring, they are also the most readily used in model validation and calibration studies. Almost all computer codes for rock mechanics analysis solve for displacements as the primary unknowns. For this reason, direct comparison between displacement instrument readings and corresponding computer code output is easily done.

The quick (instantaneous) displacement response of a rock mass to excavation is largely controlled by Young's modulus, while the delayed (time-dependent) component is controlled by rock mass (salt) viscosity. After an advance of the mining face, a period of transient creep ensues that is followed by steady state creep, provided the interval between advances is sufficient. Plotting displacement as a function of time, as measured and as modeled, readily demonstrates the agreement (or lack) between the two. Separation of data into instantaneous and time-dependent components is possible. Better agreement between model and measurement may then be obtained by changing Young's modulus and viscosity and rerunning the model. This circular exercise may eventually calibrate a model that otherwise simulates geology, excavation geometry, possible bed separation, and transient creep, but does not really validate constitutive equations at the heart of a model. Displacement data only feed one side—the strain side—of the constitutive equations. Independent measurements that feed the stress side of the constitutive equations are needed for model validation. Of course, only a properly calibrated and validated model has the potential for demonstrating "predictability." Pre-closure room monitoring should therefore provide for additional measurements, independent of displacements, that would serve model validation as well as calibration.

Stress Measurements

Stress changes are the second most common type of geotechnical data collected in monitoring programs. Stress-change data are independent of direct displacement measurements, although all instruments move to some degree according to design. Pillars between rooms are usually the regions of greatest interest for the obvious reason that they must support the overburden and thereby insure large-scale stability of the mine. Local stability and safety relative to roof falls, for example, is provided by local support, perhaps by roof bolts or by the intrinsic strength of the roof strata alone. Borehole stress gages of various types are used to monitor stress changes in pillars. An elastic response is generally assumed for stress measurement data reduction. Extension of such procedures to the viscoelastic domain would be necessary for current salt creep models used for WIPP analyses. Salt creep data may already be available from prior *in situ* stress measurements. When linked to borehole extensometer measurements, stress monitoring may provide data for technically sound model validation studies.

Other Mechanical Room Measurements

Other measurements and observations that may be relevant to purely mechanical aspects of pre-closure repository performance include roof bolt load measurement, and borehole televiewing for fracture development and bed separation. Off-the-shelf instrumentation is commercially available for making these observations.

Although not strictly a "room" measurement, observations of displacement and stress change adjacent to repository shafts are desirable, especially near aquifers above the repository horizon. Shaft tilt determined from inclinometer measurements would be of particular interest. Tilt refers to deviation of the shaft line from the vertical that may be induced by repository mining and is related to the larger issue of subsidence. Inclinometer instrumentation is relatively expensive.

<u>Subsidence Monitoring</u>

Subsidence can be divided into two broad categories: surface and subsurface ground motion. Although surface subsidence is usually implied in discussions of mine subsidence and only the vertical component of surface displacement is considered ("settlement"), the general concept encompasses both categories of ground motion. The rock mechanical features of repository performance are almost synonymous with ground motion, so subsidence is of considerable importance to rock mechanics analyses that contribute to the demonstration of computer model predictability for performance assessment. Enlargement of a mine monitoring plan to include not only surface displacement measurements, but also measurements within the rock mass between repository room level and the surface, is desirable. Surface measurements and subsurface observations would serve the twin purposes: (1) providing physical measurements for model validation, and (2) forewarning of any threatening departure from predicted performance. Empirical and rational subsidence approaches, each with advantages and disadvantages are available for subsidence analysis.

Empirical Surface Subsidence Estimation

There are several well-known empirical and semi-empirical approaches to estimating surface subsidence (settlement). The best known technique is the procedure described in the Subsidence Handbook developed by the National Coal Board in the United Kingdom. This procedure is two-dimensional and for mines using the longwall method that result in almost 100 percent extraction, unlike the room and pillar WIPP plan with about 22% extraction (SAN92). Stratigraphy and rock properties are ignored. The best known semi-empirical approach is the influence function technique which is guided by elasticity theory and then fit to existing surface measurements. Both techniques could be successfully adapted to WIPP site conditions after calibration against subsidence troughs associated with underground mines in similar geologic environments. The outcome would be a simple estimate of a WIPP surface subsidence, an estimate easily done by hand calculation. Analyses of this type have been conducted by IT Corporation for the WIPP site to support backfill studies (ITC94).

Perhaps the simplest surface subsidence estimation is to neglect volume change of the rock mass influenced by mining and then impose an angle of draw which defines the extent of subsidence at the surface. The ratio of average depth of surface subsidence to mining height is then R/[1+2(H/W)tan*] where R is the area extraction ratio (0.20 for WIPP), H is mine depth (about 2,000 ft or 610 m), W is mine width, and * is the angle of draw. This rough estimate indicates surface subsidence of about 1 ft (1/3 m), a realistic estimate in view of previous surface subsidence estimates at the WIPP site. A more formal volume conservation approach is possible through a diffusion of voids model. The advantage of empirical approaches is clearly the ease of calculation.

A serious defect associated with empirical methods is that no account can be made of subsequent measurements that are not in agreement with the empirical estimate. For example, a qualification of plus or minus 10 percent—meaning measured subsidence is expected to be within ±10% of the empirical estimate—may not be helpful if the deviation is caused by sinkhole formation. In fact, this claim is made in the Subsidence Handbook of the National

Coal Board only for coal mines in the United Kingdom where geological conditions are similar. Coal mine subsidence in sedimentary basins throughout the world is not the same and claims to accuracy based on statistical summaries of subsidence surveys in other parts of the world are not available.

Empirical methods tacitly imply subsidence occurs in the form of a smooth trough or depression over the mined region. The ground surface is assumed to deform continuously, regardless of tensile strains induced by curvature of the subsidence trough. In fact, large vertical cracks often form at the surface and subsidence may occur with fault-like motion on these induced cracks and on preexisting cracks as well. The formation of step-like features over mined regions is frequently the case and loose, unconsolidated surface burden may mask the development of cracks in shallow brittle rock strata below. Subsidence may also occur in the form of chimneys, sink holes, or pipes that propagate by caving from mine level to surface where a "glory hole" may develop. Subsurface caving may cease and the overlying strata deform by flexing to form a smooth trough or possibly a stepped trough at the surface. The presence of major joint systems and faults will also influence subsidence below and at the ground surface. Experience of nearby mines often provides valuable guidance as to the type of subsidence expected. With such experience, empirical methods may be useful, but are generally at a disadvantage when predictability from first principles is desired. For example, no empirical method is known that will indicate in advance whether trough or chimney formation is the likely subsidence mode.

Rational Subsidence Estimation

The rational approach to subsidence estimation is through a technically sound computer model—i.e., one based on fundamental principles. A full account can then be made of the effects of mining geometry (past and planned), repository stratigraphy (including aquifers), geologic structure, rock mass properties, and pre-repository stress field. In this regard, the same computer model used for room and pillar rock mechanics analysis should also be used for subsidence analyses, if indeed, model calibration and validation are required beyond that afforded by a small, two-dimensional "strip" model of a generic half-room and half-pillar. In this regard, there is always a danger of oversimplification of site details that are included in a computer model. Unless the major features of mine geometry and geology are included, the computer model will produce results of questionable utility.

Comprehensive computer modelling of mine subsidence is indeed a significant technical challenge because of the large size of the model region and the amount of detail needed, especially about rooms and pillars. Nonlinearity in the form of ductile flow of salt and possibly caving after creep rupture complicates the constitutive description as do strata interfaces, clay seams, and the presence of other rock types, some of which are water-bearing. However, some large-scale three-dimensional finite element modeling has been done, so there is a possibility for incorporating stratigraphy into an improved model for subsidence analysis. The outcome would be a rational forecast of surface and subsurface displacement, strain and stress field changes as time passes and operations continue during the pre-closure period. Direct and timely comparisons between measured and simulated station histories could then be made, and significant deviations could be easily identified for further investigation. Such a forecast could also be used to plan a network of surface subsidence stations.

Subsidence Instrumentation

Surface subsidence is often monitored by repeated level surveys over a grid of survey stations extending beyond the limits of expected surface movement above the mined area. A rule of thumb for spacing of surface survey points is to limit spacing to 1/20th of the mining depth. This rule suggests a maximum spacing of about 100 ft (31 m) at the WIPP site. The rule is based on differences between stations required to resolve horizontal surface strains. Frequency of surface surveys should be appropriate to the mining rate and the amount mined between surveys. The minimum amount of incremental extraction underground should be determined for this purpose. Because of salt creep, this amount will be time-dependent. Surveys more frequent than the rate of extraction multiplied by the minimum required for detection may be of questionable benefit in relation to cost. In this regard, the expense of high precision leveling between stations may not be warranted in view of computer code scatter and variability in the amount of subsidence forecast by empirical methods. Level surveys to millimeter accuracy would not be informative when predicted subsidence varies by tens of centimeters.

A common practice for subsidence surveys in the mining industry is to use aerial photography and carry out surveys annually. During the early years of repository operation, quarterly surveys may be desirable. Subsidence determination from aerial photographs in the form of present and past contour plots may be substituted for leveling.

Subsidence instrumentation could be installed in boreholes below ground surface as well as at the surface above the repository. The first would require reconsideration of boreholes as threats to repository integrity. Some boreholes are planned for hydrologic monitoring. This

suggests that boreholes of limited depth that do not penetrate the repository horizon or the zone of influence of the repository rooms may be acceptable with proper seals.

Several types of instrumentation could be installed in boreholes for monitoring subsurface subsidence. Two borehole techniques used successfully in the past are cross-hole seismic monitoring and time domain reflectometry. The principal objective of both is to detect caving above the mining horizon. Cross-hole seismic wave velocity decreases dramatically as the caved zone propagates upwards between instrumentation holes. An array of geophones in boreholes and at the surface would allow for general monitoring of "rock talk," that is, micro-seismic events associated with rock mass motion induced by repository mining and operation. The location, amplitude, frequency, and other characteristics of the mining-induced seismicity could be helpful in identifying the onset of anomalous rock mass behavior. Investigation of the phenomena during the pre-closure phase would be helpful in determining applicability during the post-closure phase when direct access to the repository is not possible. The second borehole method involves installation of an electrical conductor that subsequently breaks with advance of the cave zone. Signal time to the break is measured and the cave height determined by time domain reflectometry. Establishment of successful borehole monitoring procedures during the pre-closure phase would be particularly advantageous during the post-closure phase.

Geophysical Monitoring

Several geophysical phenomena can be utilized to characterize subsurface features which are dependent on the physical composition of the subsurface materials and include, but are not limited to: conductivity, magnetic susceptibility, dielectric permittivity, radioactivity, density, rigidity and morphology. These physical parameters control geophysical observations which can be exploited to monitor target objects and phenomena. Several geophysical sensors are available to directly or indirectly measure subsurface geophysical phenomena and are described below.

Passive geophysical techniques are used to measure fields caused by the presence of anomalous bodies, not those caused by external sources. These observations include the Earth's magnetic field, gravitational fields, and temperature, for example. Active geophysical techniques are based on the measurement of the response of the media to external sources of excitation. Examples include ground penetrating radar, induced conductivity, acoustic and seismic methods, and nuclear activation techniques. Active geophysical methods are distinguished by having a source and receiver, whereas passive methods only have receivers.

In order to evaluate the performance of the facility, a monitoring system will need to be highly sensitive to changes in subsurface conditions. The sensitivity and subsequent effectiveness of monitoring techniques can be significantly enhanced through the use of differential measurement techniques. With differential methods, redundant, identical measurements are carried out over regular time intervals. The complex features contained in many types of geophysical data are thus reduced through numerical comparison of previous measurements. The collection and analysis of monitoring data with identical instrumentation and configuration will serve to enhance the observation of temporal changes in repository conditions.

Various geophysical phenomena can be exploited in order to evaluate the state of the WIPP repository after closure. Existing sensors are available to make highly accurate and relevant measurements which can be used to evaluate the performance of the facility. Further, the geophysical sensor industry is very active in developing new and more sensitive instruments which will likely be applicable to post-closure monitoring. For the purpose of current planning, however, only existing sensor technologies need be considered.

11.3 POST DISPOSAL MONITORING

11.3.1 <u>Jeopardizing Waste Isolation</u>

11.3.1.1 Introduction

Data collected post-closure could be used to compare the predicted repository conditions to the actual repository conditions. Subsequently, deviations in conditions from those of the predictive modes could be used to validate or dispute the validity of the predictive constructs, and to further quantify expected future performance.

To explicitly address the potential detrimental effects of environmental monitoring, the EPA stated in §191.14(b) that any post-closure monitoring be conducted with technologies that do not jeopardize the isolation of the waste. There are several ramifications of this requirement which affect the conceptual and operational aspects of post-disposal monitoring.

11.3.1.2 Ramifications of Non-Threatening Monitoring

The explicit requirement to perform all monitoring activities without jeopardizing the integrity of the repository has physical, conceptual, and logistical ramifications. First, this requirement may limit or exclude the use of direct monitoring techniques within the repository or within boreholes placed in the strata above the repository. It is likely that this requirement will limit most or all sensor deployments to the surface, and impose strong reliance upon remote monitoring technologies.

Second, the spatial separation between the monitoring sensors and the repository, in excess of 2000 feet, increases the need for highly sensitive instrumentation. High sensitivity is required due to the decrease in amplitude of most geophysical observations with increased sensor-to-source distance. The need for enhanced sensitivity may require monitoring plans to incorporate advanced or innovative techniques, such as differential measurement strategies.

Third, the requirement of safe and remote monitoring at WIPP may make the evaluation of important repository performance parameters difficult, ambiguous or impossible to perform. In such cases, observable parameters may be identified which correlate with performance-sensitive un-observable parameters. As such, an evaluation of critical performance parameters should be performed which includes the ability of available monitoring technologies to make accurate parameters estimates. In cases where significant performance parameters cannot be determined through monitoring, correlated parameters should be identified, if possible.

Direct measurements of important parameters within the repository after closure can be performed only if there are no detrimental effects to the repository caused by the monitoring activity. Presently, technologies are being developed which may allow for monitoring directly within the excavated rooms without a physical connection between the repository and the surface.

Post-closure monitoring must be comprised of existing and available sensing and data collection technologies. While a new technical development may provide additional options in the future, present requirements must be met with present technologies.

The restrictions and goals of post-closure monitoring lead to the likely use of surface or near surface monitoring techniques. Given the parameters and correlated parameters of interest discussed above, the employed surface techniques will predominantly exploit geophysical measurement and monitoring technologies as described in Section 11.3.2.

11.3.1.3 Bore Hole Techniques

The placement of sensors within bore holes located above the repository represents a potential monitoring advantage compared to surface deployed monitoring equipment. This potential improvement in monitoring performance comes from the geometrical aspects of borehole techniques. First, borehole sensors, by their very nature, can be located closer to the repository. Depending on the maximum safe depth of the borehole, significant improvements in target proximity can be achieved. This is particularly important in repository monitoring, where measurement of small variations in background conditions are desired. Physical phenomena such as temperature, electromagnetic field strength, gravitational field strength, and elastic waveform amplitudes decay rapidly with distance. Thus, monitoring capabilities may be significantly improved through the deployment of down hole sensors.

Second, the effectiveness of many geophysical techniques is diminished due to the contamination of geophysical data by noise. The detection of features in geophysical data which can lead to the estimate of targeted performance evaluation parameters is based on both the strength of the observational feature as well as the degree of noise in the data. The important factor in environmental monitoring is thus captured in the signal to noise ratio (SNR). Subtle important features in monitoring data may be used for parameter estimation if noise levels are sufficiently low to achieve a high SNR. Bore hole sensors, by their isolation and distance from the surface, can achieve extremely low noise conditions.

Third, the geometry of geophysical monitoring arrays, through the deployment of bole hole sensors, can have a positive impact on the post-closure monitoring program. The relatively planar feature represented by the ground surface above the repository limits geometrical observational considerations. Bore holes, conversely, can be optimally positioned to maximize observation resolution. As mentioned previously, cross-hole seismic measurements made in bore holes straddling the repository may be highly effectual in monitoring deformational changes in repository structures.

11.3.2 Geophysical Methods

In this section a series of possible monitoring techniques are discussed which are separated into three categories depending on the repository attribute targeted by the monitoring activity. These categories include; direct measurements, geoelectrical properties, and geophysical properties. The associated technologies which can be used in these areas are listed below:

- Direct Measurements
    - Surface Subsidence
    - Direct Repository Monitoring
    - Groundwater Monitoring

- Geoelectrical properties
    - Electromagnetic
    - Resistivity

- Geophysical properties
    - Seismic
    - Gravity
    - Magnetic

11.3.2.1 Surface Subsidence.

Pre-disposal subsidence monitoring was discussed in Section 11.2.2.3. This is a simple technology by which subsurface repository characteristics are estimated through the collection and analysis of data describing the changes in the surface topography above the repository. Relative motions of surface can be upward or downward, and are referred to as uplift and subsidence, respectively. Typically, a reference point within the study area is assumed to be constant, and all motions are calculated relative to this pseudo-stationary point. Such surveys are relativistic, and do not attempt to describe the regional uplift or subsidence trends overall. The technology utilizes relative vertical height measurements between benchmarks located on the ground surface. Various conventional methods are used to make these measurements throughout a network of stations over regular time intervals. Through the simple processing of these data, a deformational history of the surface can be determined. With existing technologies vertical motion of the order 0.01 inch can resolved.

Since subsidence can be caused by a variety of factors including mining, water extraction, dissolution and hydrocarbon production, the determination of the cause of subsidence observations can be highly non-unique. Further, the spatial and temporal resolution of the parameters affecting the surface observation may be lower than is required to make useful conclusions regarding the repository performance.

While subsidence monitoring is attractive due to operational and financial considerations (subsidence monitoring is simple and inexpensive), the measurement of the deformation history of the ground surface over 2000 feet from the repository, may not have the required sensitivity to assess desired performance characteristic parameters.

11.3.2.2 Direct Repository Monitoring

The most effective way to monitor post-closure repository performance is to make direct measurement of the repository. Unfortunately, no viable technologies are presently available to connect the sub-surface repository sensors systems to the surface without direct physical connection. The risk of jeopardizing repository integrity by creating a borehole to the repository or by establishing a cable connection from the surface are unacceptable. Thus, direct repository monitoring must be accomplished without direct connection.

Currently, both industrial and governmental groups are developing technologies which may facilitate remote communication between the ground surface and the repository. Both very low frequency (VLF) and ultra low frequency (ULF) electromagnetic propagation methods are being developed. If this technology matures significantly, then it may provide a means to deliver direct repository measurements for performance evaluation.

11.3.2.3 Groundwater Monitoring

Groundwater monitoring is a form of direct measurement of environmental conditions which may be useful for the evaluation of the WIPP repository performance. Groundwater monitoring consists of the selection of borehole locations, drilling of the boreholes, groundwater well installation and sampling.

Prior to installation of the monitoring wells, depth and diameter of the well should be established to meet the specific monitoring needs of each location. Specification of adequate well depth and diameter depends on the purpose of the monitoring system and the geologic system it is monitoring. Wells of different depth and diameter can be employed in the same groundwater monitoring system. Varying the depth interval covered by the well screens in several wells, or in one multi-level well, can help to determine the vertical distribution of hydraulic heads and the levels at which contaminants are present. The quality of the groundwater may vary with depth due to several factors, such as the density of the contaminant-water solution, lenses or layers of varying permeability, and geologic features that may form barriers diverting fluid flow. A fully penetrating well cannot be used to quantify or vertically locate a contamination plume, since groundwater samples collected in wells that are screened over the full thickness of an aquifer will be representative of average conditions across the entire screened interval. However, fully penetrating wells can be used to establish the existence of contamination in an aquifer.

The decision concerning the depth of placement and length of the well screen is based on: aquifer depth, thickness, and uniformity; head distribution and estimated flow in the aquifer; permeability of the aquifer; specific yield of existing wells; anticipated depth, thickness, and characteristics (e.g., density relative to water) of potential contaminants; expected fluctuation in groundwater level; the expected presence of volatile organic compounds; and the type of borehole geophysical logs expected to be deployed.

Sampling strategy decisions, including the amount of flushing a well should receive prior to sample collection and the selection of sampling devices, depend on the intent of the monitoring program and the in situ hydrogeologic conditions. Programs to determine overall quality of water resources may require long pumping periods to obtain a sample that is representative of a large volume of that aquifer. The pumped volume may be specified prior to sampling so that the sample can be a composite of a known volume of the aquifer. Alternately the well can be pumped until the parameters such as temperature, electrical conductance, and pH have stabilized. Sampling instrument selection is dependent of several factors including cost, power requirements, sample isolation requirements, decontamination requirements, sample volumes, etc. Bailers, suction pumps, gas-lift samplers, and submersible pumps may be applicable.

Several factors will contribute to the potential usefulness of groundwater monitoring techniques in providing data for the evaluation of repository performance. These include, but are not limited to: the number, type, and depth of wells located above and around the repository; the chemical and radiological analyses performed on extracted samples; and the time interval between subsequent sampling events.

One groundwater monitoring technique which has been employed at other locations involves the use of synthetic tracers. The State of New York Department of Ecology (NYDEC) is interested in using synthetic tracers to "spike" individual landfill cells to facilitate the detection and identification of future leaks. To support this objective, the NYDEC sponsored a detailed tracer study, designed to evaluate the relative characteristics of numerous tracers in the laboratory and field. Work included laboratory tests, several natural gradient tests and recirculation/injection tests. Numerical simulations were performed to analyze the collected data. Similar technology has also been used to detect and identify leaks from large petroleum tank farms.

Since the travel time for non-sorbing tracers is shorter than for radionuclides subject to chemical retardation, such tracers could conceptually provide a leading indicator for radionuclide release from the repository. This approach is consistent with the concepts outlined by EPA in 1985 and discussed in Section 11.1.1 above. Depending upon the results of ground-water flow calculations, various tracers might be placed in the repository at closure and down stream monitoring for tracer migration in the marker beds near the repository horizon be conducted at the site boundary. This might be particularly useful in assessing any detrimental effects caused by waterflooding of vicinity oil fields to enhance recovery.

11.3.2.4 Electromagnetic Conductivity

Electromagnetic (EM) waves can be used to determine electrical properties of subsurface materials within the earth. Techniques based on propagating electromagnetic energy into the earth and measuring responses to that input have been used extensively in geophysical exploration and characterization applications for several years.

When an alternating current is applied to a looped transmitter antenna, it acts as an alternating magnetic dipole source. The resulting alternating magnetic field, the primary field, induces current flow in subsurface conductors. Good conductors, like buried metal objects or saline ground water, produce strong induction currents that decay more slowly than induced currents in poor conducting materials. The induced current in the buried conductor thus produces a secondary field observed at the surface.

Since variation in magnetic permeability in the ground is small, for a fixed frequency and fixed transmitter-to-receiver coil distance, the fields produced by the induced electric currents will be proportional to the conductivity of the subsurface. The most common field measurement for these systems is the ratio of the primary to secondary magnetic field. Different relative orientations of transmitter to receiver coils respond differently depending on the spatial geometry of the conductive bodies. In particular, the quadrature component of the secondary field is considered most appropriate for measuring broad anomalous conductive layers like contaminant spills. In-phase component measurements, on the other hand, are more sensitive to the effects of local highly conductive objects like buried metal objects.

Depth of penetration and resolution of the EM induction depends on several parameters, including average ground conductivity, source power, source frequency, and antenna spacing. Systems used in a depth-sounding configurations, with expanding source to receiver spacing, can estimate the depth to anomalous conducting bodies. In a profiling mode, the source-to-receiver spacing is fixed and the area is surveyed on grid lines. This type of survey can produce 2-D surface anomaly maps.

EM systems can be used to make estimates of the conductivity of the subsurface. In turn, these estimates can inferentially be related to subsurface geophysical and geochemical properties such as porosity, permeability, and concentrations dissolved electrolytes, for example. The EM response of the subsurface is highly sensitive to water content and thus may be useful in the mapping of aquifers and brine bodies. Highly conductive metal objects, such as pipes, metallic debris and structures are readily detected and mapped.

EM techniques have operational limitations inherent to active geophysical techniques, including the accurate positioning of source and receivers. EM techniques have the further weakness of having restricted resolution due to the averaging of the media conductivity between source and receiver. The operational concerns at WIPP must be investigated to determine the specific usefulness of EM techniques in assisting with repository performance evaluations.

11.3.2.5 Resistivity

Like electromagnetic conductivity methods, resistivity techniques represent well established methods for determining the electrical properties of the subsurface. Resistivity is the inverse of conductivity, and is thus affected by the same factors described for the electromagnetic conductivity technique above.

The resistivity technique utilizes a series of electrodes on the surface. Two electrodes are energized to establish a electric current in the earth between them and two other electrodes are used to measure the potential developed by the first pair. By varying the number, type, and position of the electrodes, as well as varying the input currents, subsurface resistivity parameters can be estimated.

Resistivity methods can be used to determine the thickness of electrically distinct strata as well as the location of aquifers or brine layers.

11.3.2.6 Seismic Techniques

Seismic techniques exploit well understood elastic wave propagation phenomena and can be used for a variety of applications ranging from the determination of the depth, thickness and composition of geologic structures, to the identification of subsurface fracture zones or voids. The subsurface is mapped by modeling measured seismic observations in terms of the travel times and shapes of the recorded waveforms. The paths, velocities and amplitudes of the waves are controlled by the distribution of the elastic moduli of the media, including the bulk modulus (volumetric response), shear modulus (torque response), and Young’s modulus (stretch response).

Oil and gas industry seismic techniques are generally based on the recording and interpretation of reflected and/or the refracted waves generated by controlled sources. Various forward and inverse waveform modeling procedures have been established to process data for interpretation of the sub-surface geologic structure. Data are collected on geophones located either on the surface or in boreholes in one, two, or three-dimensional configurations. The wave propagation energy source is generally a dropped weight or controlled explosive. A wide variety of source and receiver configurations can be utilized to exploit various wave propagation effects.

Seismic methods based on the observation of reflected waves and refracted waves (bent due to Snell's Law) are regularly used to map hydrocarbon reserves, to locate aquifer boundaries, and make estimates of subsurface velocity and density parameters. These highly developed methods may be applicable to the evaluation of the performance of the WIPP site after closure.

Additionally, seismic surveillance techniques may assist in determining the post-closure repository performance. These methods are based on the continuous monitoring of ground motions on the surface or in boreholes located above and around the repository. Best known for detecting and locating earthquakes, seismic networks can also be used to locate and characterize microseismic perturbations within the repository.

11.3.2.7 Gravitation

The gravitational method involves systematic measurements of small deviations in the earth's gravitational field. Observations of the gravitational forces, described by Newton's Law, are sensitive to mass and density variations in the lithosphere. Gravity surveys can be used to detect and map structural changes in the subsurface, such as faulted or bending strata. Gravimeter data is collected on a grid and interpreted to provide a broad picture of the density distribution of the media.

At WIPP, it is unlikely that gravity variations will provide sufficient spatial or temporal resolution of parameters which describe the repository performance. However, this technique may be useful in constructing a comprehensive and accurate understanding of the substructure when combined with the data from other sensors.

11.3.2.8 Magnetization

Like the gravity method described above, the magnetic method takes advantage of naturally occurring force fields. An additional similarity is that, with the magnetic method, small deviations in the force field, relative to the primary field, are required. Anomalies in the magnetic field of the earth provide an effective geophysical observation to be exploited for the detection and characterization of underground buried ferrous objects. This phenomenon is based on the fact that some ferromagnetic minerals (magnetite, ilmenite, pyrrhotite) have magnetic susceptibilities more than 10,000 times that of non-ferromagnetic materials.

Materials composed of ferromagnetic minerals have elevated bulk magnetic susceptibilities which can alter the magnetic field. Variations in the magnetic field can be measured and modeled to determine the relative distribution of ferromagnetic materials below the surface.

Clearly, magnetic techniques are only useful in detecting and characterizing ferromagnetic objects, typically those made of iron or steel. At WIPP, the magnetic method, by itself, will not provide a robust or comprehensive technique for assessment of the repository post-closure performance. However, a magnetic field survey may provide important information about the distribution of subsurface materials which may simplify, through modeling, the interpretation of effects observed in other data types.

11.4 CONCLUSION

As technological advances continue, the options for monitoring will expand. However, fundamental aspects regarding the measurement of the environment at WIPP will remain indefinitely. These aspects are related to the basic physics of the repository and include, for example, the location of the repository structures, the employed construction techniques and materials, the backfill composition, and the type, location, and quantity of naturally occurring brine. An evaluation of critical repository performance parameters suitable for monitoring must be performed to define the monitoring requirements and this evaluation is included in the compliance criteria of 40 CFR part 194.

Monitoring at WIPP may include measurements of the repository itself as well as measurements of the surrounding environment. Sensors may be deployed to perform a variety of geophysical, meteorological, and radiological measurements, and may include, for example, seismometers, magnetometers, ground penetrating radar, pulsed induction sensors, conductivity sensors, resistivity sensors, acoustic devices, bench mark leveling devices, global positioning system equipment, groundwater sampling devices, radiation sensors, and meteorological instruments.

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